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Modular Inspection Equipment Design for Modular Structured Mechatronic Products – Model Based Systems Engineering Approach for an Integrative Product and Production System Development

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Abstract

Quality control is an essential part of the production of modular mechatronic systems. Especially the quality inspection of the overall system at the end of the production is of extraordinary importance. The associated inspection equipment can also be a mechatronic system, which is often explicitly designed and manufactured for one product with a large expenditure of time. In order to have the needed inspection equipment ready by the start of production (SoP) and to consider additional requirements to the product, which are produced by the inspection equipment concept, an integrative mechatronic product and inspection equipment development procedure is needed. Furthermore, the inspection system has to consider the modularity of the system and often has to be designed in a modular way. Nowadays, the development of complex mechatronic systems is often carried out with the help of model-based systems engineering (MBSE) methods. Consequently, the inspection equipment should also be designed with the help of MBSE. This paper describes an integrative product and inspection equipment procedure for modular mechatronic systems with the help of MBSE. Especially the peculiarity of the modularity is described and validated with the help of an application example.

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1. Introduction

Nowadays, most of the modern technical products are mechatronic systems. Mechatronic systems can be described by the close interaction of mechanics, electrics / electronics, control engineering and software engineering. Therefore, the interdisciplinary collaboration in the design and the development of such systems becomes more and more important [1]. Currently, the global competition can be characterized by the high speed of innovation, shortened product life cycle as well as increasing customer expectations for performance, quality and price of products [2], [3]. Furthermore, a global distribution of the production of mechatronic systems becomes more and more common [4], [3]. Consequently, the product complexity increases due to the increase of the product functionality.
In order to meet customers' requirements, these mechatronic systems are often built in different variants [5], [6], [7] and/or in a modular way. This modular structure of the product additionally increases the complexity of the development.

As a result of an increase in product quality, the quality inspection is becoming increasingly important during the production of mechatronic systems. In particular, the quality examination of the overall system at the end of production is extremely important. The increasing complexity of mechatronic systems leads to an increasing complexity of their inspection equipment. Most of this inspection equipment is also complex mechatronic systems.

When the product is a modular mechatronic system, the inspection equipment itself has to consider this modularity. Furthermore, there can be additional reasons for the modularization of the inspection equipment, e.g. for the expendability. This allows companies to adapt the inspection equipment to different sales numbers of the product or to inspect the product in different countries. Another reason can be that different varieties of products have to be inspected in different countries.

Due to the complexity of the modern mechatronic systems, the product and the production system must be designed and developed integratively, in order to match optimally with each other [8], [1]. Especially the development of the product inspection equipment – because of the numerous existing interfaces and interactions between it and the mechatronic product – has to be considered.

Regarding the shortened product life cycle, simultaneous engineering approaches are typically used. The production system and its quality examination components – mainly the inspection equipment – have to be designed and developed simultaneously with the product development. The development of inspection equipment has to be started at an early development phase of product development, in order to be ready by the start of the production time. Moreover, the development of inspection equipment typically results in additional product requirements, which have to be communicated back to product development. These requirements can only be considered if the inspection equipment development starts in an early phase of the product development.

This paper shows a systematic considering the modular structure of a modular mechatronic system during the development of an inspection system. It is shown how to modularize an inspection system with the support of MBSE-methods. Additionally, an integrative product and inspection development process is shown. The systematic will be applied and described by an application example, which is the innovative modular inverter system (IMIS) of the company KEB [9].

2. State of the Art and Need for Action

This chapter describes the related state of the art. It starts with a description of general trends in the product development and production. An introduction to the integrative product and production system development to the mechatronic design with the help of MBSE is given. Furthermore, the state of the art for different types of inspection planning is presented. At last the need for action is illustrated.

2.1. State of the Art

Trends in product development and production: In order to handle the different product variants, mechatronic systems are often developed and built in a modular way. This modular structure of the product additionally increases the complexity of the product and the quality inspection system regarded from a development point of view.

Integrative product and production system development: One of the most applicable approaches is the integrative product engineering process according to Gausemeier et al [10]. This approach considers the product development process, especially for mechatronic products, not as a strict series of phases and milestones, but as an interplay of tasks. The Gausemeier et al. approach describes the product engineering process with a procedure model, starting with a product or business idea and ending with series production. It covers three main areas: strategic product planning, product development, and production system development. These three main areas have to be worked out iteratively. The important proposition for this paper is that especially the product development and production system development should be worked out in parallel and need to be matched, because the inspection system is part of the production system. [10]

Mechatronic design with MBSE: As product and production system development of mechatronic systems cannot be assigned to a specific discipline, there are high demands regarding the communication and cooperation between the involved multidisciplinary experts [11]. Successful product development projects are increasingly depending on the combination of different skills in an interdisciplinary development team [6]. Nevertheless, it is a challenge to combine the different perspectives of the various involved disciplines on the same system to enable a collaborative work between them [11]. This requires systems thinking and an understanding of the system as a whole and not with a discipline-specific view on the system [12]. In order to meet these challenges during the design and the development of complex mechatronic systems, developers often use and should use methods of MBSE for complex mechatronic systems, e.g. aerospace and automotive [13], [14], [15], [16]. It intends a holistic system description with a system model and system analysis based on models, beginning in the early phases of product development and continuing throughout the whole product life cycle. Because of this, the mechatronic systems design process is changing from a document-based process to a model-based one.

The system model constitutes the basis for communication and cooperation in a multidisciplinary project environment; it helps to reason about a problem and pursues the goal of controlling product complexity by being transparent [17]. The objective is to gain transparency by describing the aspects of a system in suitable diagrams, which are linked to each other and especially to the requirements to ensure traceability.

Different approaches for MBSE exist. A very common and widely spread language is the Systems Modelling Language (SysML) [13]. In this paper, the specification technique CONSENS "Conceptual Design Specification Technique for the Engineering of Complex Systems" as an example of MBSE method will be discussed. The presented approach, however, can also be implemented by using SysML or other MBSE approaches.

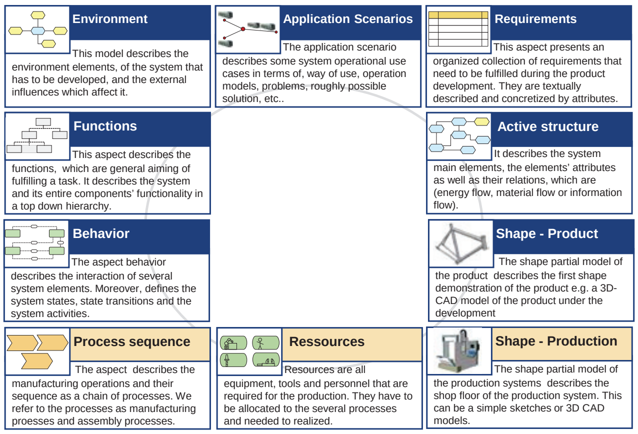


Fig. 1. Partial models for cross-domain description of the principle solution of mechatronic systems and the production system according to [18]

CONSENS describes the principle solution of a mechatronic system and its production system with ten coherent partial models as shown in Fig. 1. The product is described by seven partial models: environment, application scenarios, requirements, functions, active structure, shape, and behavior (blue). The associated production system is described by three partial models: processes, resources and shape (beige). [19]

Actually MBSE is used to handle the complexity of the overall system, but the consideration of variants with MBSE is not very common. One known application is [20], where especially the consideration of the development artifacts from variants is described. An application with MBSE, that shows the transition from product variants to inspection equipment variants, which considers the product variants, is not known.

An integrative view of product and production system is possible as shown above, but it is assumed that the resources in the production – like the inspection system – still exist and must not specially be developed for the product.

The conventional inspection planning: inspection planning generally describes the planning of the required quality control steps during the production process, which starts with components delivery and ends with product delivery [21]. The main aim of inspection planning is the ensuring of predefined quality requirements of the product [22], [23]. According to Linß [23], the inspection planning is responsible for planning the required inspection steps during the different production steps or during the provision of a specific service. The inspection planning itself contains the following main components: inspection procedure, inspection steps, inspection instructions, and inspection methods [23].

A systematic creation of an inspection plan ensures a proper quality of the product. The implementation of an inspection plan depends on advanced knowledge about the usage and the functionality of the product, production process, production documents, technical specification of production, and inspection equipment [24], [21].

In the conventional inspection planning, the creation of the inspection plan has to be carried out in parallel with the creation of the production plan. This has to be done immediately after the construction and development of the product [25], [26], [27], [22]. So, an integrative approach is not considered. In the conventional inspection planning it is assumed that the examinee is a component or a mechanical part. The modularity is considered neither from the product nor of the inspection system.

Integrative product development and inspection planning: The inspection planning should not be developed separately from other activities of the product development. Moreover, it should be considered as an integral part of the product and the production system [24], [28]. In order to increase the efficiency of the inspection planning, the product quality critical properties and their inspection equipment should be tackled at an early stage of the product development process [29], [25], [6]. In the mentioned references it is reported that it has to be done in an integrative way, but it is not described how to do it. The modularity is considered neither from the product nor of the inspection system.

Further inspection design methods: Regarding the inspection planning further documents exist [22], [30], [31], [32], [33], [34], [35]. In these references the early planning, the mechatronic or the modularity is partial considered, but an integrative product and inspection equipment design is not considered. Likewise the integrated design of product and inspection system at an early development phase with methods of MBSE is not considered.

2.2. Need for Action

The state of the art investigation shows that there is a need for a design methodology to overcome many challenges during the inspection equipment development process. The main challenge is “complexity and variants handling” of the product, which exist due to the growing complexity of mechatronic systems and increasing number of mechatronic product variants. Furthermore, following the approach of integrative development of product and its inspection equipment, the inspection equipment development fulfils two important requirements: the inspection equipment will be ready by the SoP “Start of Production” and the requirements, which are driven from the inspection equipment back to the product, will be considered. Unfortunately, the existing integrative development approaches consider that the inspection equipment are existing in market and ready to be ordered, therefore there is a need to overcome this inadequacy. A further challenge is given due to the complexity of the modern inspection equipment. They are often used, not only for the mere examination of the product quality, but are also used for the product adjustment [36] during the end of production inspection e.g. sensors calibrations [36]. Therefore, there is a need for a design methodology which is able to handle the complexity, the modularity, and the extendibility of the modern inspection equipment. Hence, in this paper the essential part of the design of modular inspection systems for modular mechatronic product will be described with the help of a MBSE method.

3. Solution Approach

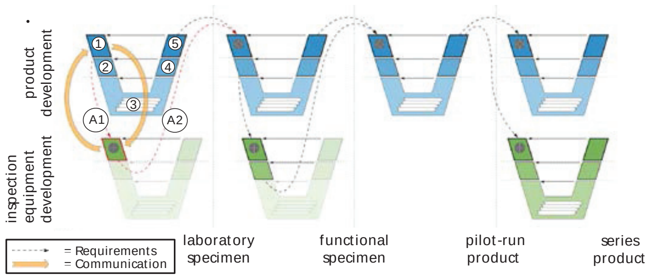
This chapter describes a generic development process for the integrative development of product and inspection equipment (Fig. 2a). Furthermore, a procedure model is shown (Fig. 2b), which demonstrates the overall procedure consistent with the integrative development process. Due to this overall procedure model, phase 2 – the design of the inspection equipment – is described in a detailed procedure model (Fig. 3a).

3.1. Integrative Development Process and Overall Procedure Model for Inspection Equipment Design

Mechatronic products are regularly developed according to the "Design Methodology for Mechatronic Systems" [2]. The design methodology describes a generic development procedure of mechatronic systems according to the V-Model (similar to the first blue V in Fig. 2a). The V-Model starts with the product requirements. The further steps are: the overall system design (1), specification of sub-systems (2), domain-specific development (3), integration (4), and (5) test (arrows from the right to the left side of the V-model). The product concept maturity increases through several iterations through the V-models, which is herein after referred to as (blue) V-series macrocycles. [2]

Based on this V-model, a modified procedure is shown in Fig. 2a. The modified procedure consists of two rows of V-macrocycles: a row with the product V-models (blue) and a row of inspection equipment V-models (green). This integrative product and inspection equipment development procedure is thinkable in further similar ways. The important idea is the interplay between the design of the product and inspection equipment and their development. In this way it is possible to derive requirements from the product to the inspection system (A1) and from the inspection system back in the product development (A2). A detailed description of this procedure is given in [37].

According to the integrative procedure (Fig. 2a) an overall procedure model for inspection equipment design is shown in Fig 2b. The start point is the product concept with the specification technique CONSENS (mark (1) in Fig. 2a and 2b). In **phase 1** the requirement analysis for the inspection equipment is executed as desribed in [37]. **Phase 2** is the main focus of this paper in which the design of the inspection equipment is also worked out with the specification technique CONSENS. In **phase 3** the product requirements, which come from the inspection equipment, have to be identified. Phase 3 is corresponding to the requirements, which are generated from the inspection equipment system design to the product development (see Fig. 2a, (A2)).



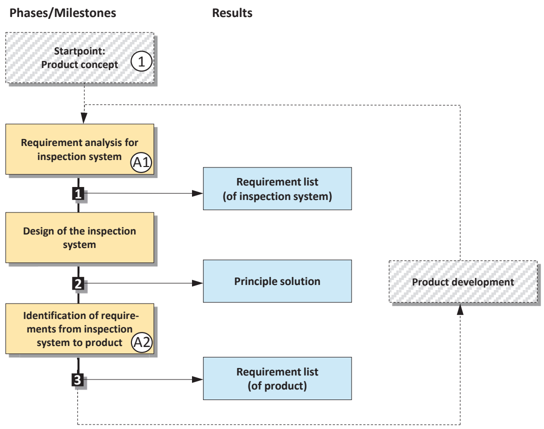
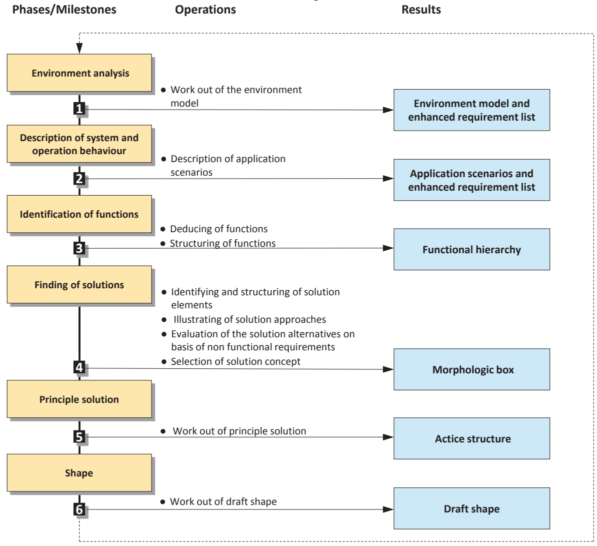


Fig. 2. (a) Integrative product and inspection equipment development procedure ;
(b) The overall procedure model of inspection equipment design.

3.2. Creation of the Inspection System

In this subchapter the design of the inspection equipment is described. It is assumed that the product design was made with the specification technique CONSENS (gray box (1) in Fig. 2b) and the requirement analysis was made according to [37] (phase 1 of Fig. 2b). The procedure model of the inspection equipment design, which is a detailed description of phase 2 of Fig. 2b, is illustrated in detail in Fig. 3a. The procedure is roughly likewise the design of a product with the specification technique – with some exceptions.

As a basis for the procedure, according to Fig. 3a, it is assumed that the functions of the modular product are existing and marked as mandatory, optional, alternative and multiple functions. Mandatory functions are always included in the product. An optional function can exist in the product, but must not exist. It depends on the required configuration. If an alternative function (1.x.y) exists in the product, only one of the sub-functions can be selected (in case of Fig. 3b, a or b). Multiple functions indicate that this function must be inserted minimum once or several times in the product. The notation of these functions is shown in Fig. 3b and extends the previous notation of the CONSENS functional hierarchy.



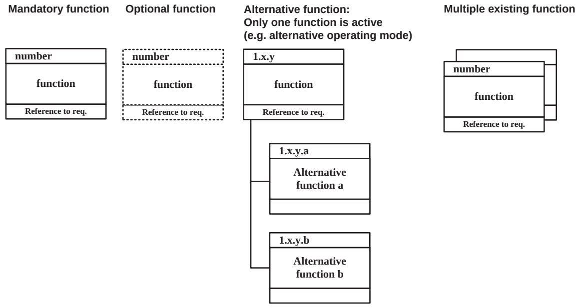


Fig. 3. (a) Procedure model of inspection equipment design (Phase two of Fig. 2b in detail); (b) Notation of the functions

In **phase 1** (Fig. 3a) of the design an environment model of the inspection equipment for the overall inspection of the mechatronic product is generated. Due to this environment model dedicated requirements are deduced to the inspection equipment. In **phase 2** application scenarios of the inspection equipment are described. Application scenarios describe the system and operation behavior and the interaction of the inspection employees with the inspection system as good as possible in this phase. Especially the interaction of inspection employees with the inspection system cannot be described completely, because at this stage it is unclear which function is accomplished by an inspection employee and which by the inspection system itself. Mainly because of this reason the return from phase 6 to phase 1 is scheduled. Depending on these scenarios further requirements for the inspection equipment are deduced. The requirements of phase 1 and phase 2 are supplemented in the requirement list. The objective of **phase 3** is to identify and to structure all functions of the inspection equipment. Therefore the requirements are divided in non-functional and functional requirements. All functions of the product have to be regarded as functional requirements. Those functions that have to be inspected become functions of the inspection equipment at the end. These relations are listed in Table 1:

Table 1: Relations between product functions, inspection equipment functions and number of functions of the inspection equipment

Function type of the product	Number of inspection equipment functions relating to one product	Σ Inspection equipment functions minimal to Σ Inspection equipment functions maximum
Mandatory	1	1 to n
Optional	1	1 to n
Alternative (number of alternatives = a)	a (one function per alternative)	a to $a*n$
Multiple (max. number = m)	1 to m (one function to max. m functions)	1 to $m*n$

Table 1 is described in the following lines: In the first column the function type of the product is listed. The second column shows how many inspection equipment functions are needed to inspect one product function – assuming that one product after another is inspected (no simultaneously inspection of products). If the inspection

system has to inspect more than one product simultaneously or one or more functions, the number of the second column has to be multiplied with *n*. *n* describes the number of products to be inspected simultaneously. The third column shows the result of the minimum and maximum calculated number of resulting functions from one product function to be inspected.

One mandatory function of the product results in exactly one function of the inspection system, if the inspection system has to inspect one product after another. If the inspection system has to inspect *n* products simultaneously, the function of the inspection system must exist *n* times, too.

If one function of a product exists *m* times (more than one time) it is called a multiple function. It is possible to inspect these functions in series one after another or to inspect them simultaneously. Therefore the result of the possible number of inspection equipment functions for that case is 1 to *m* (column 2). If all of these multiple product functions have to be inspected simultaneously and *n* products have to be inspected simultaneously, a maximum number of functions of the inspection equipment *m***n* functions of the inspection system are resulted and needed. One possible reason is to accelerate the inspection time for more output per time unit.

Additionally in some cases the inspection equipment can contain optional functions by itself, for example if special functions of the inspection equipment are needed for different countries – maybe because a product configuration is not built in this country and one function to be inspected does not exist in this country.

A concept making likewise classifications (as here) in mandatory, optional, alternative and multiple functions can be found in [38] (foda method). The main difference to this literature is that there are no functions; but features are classified in feature trees (a feature must not be solution neutral).

From all further functional requirements, which are not resulting of a product function, further inspection equipment functions are built as well. To structure the functions of the inspection equipment in order to find structured solutions for these functions later a functional hierarchy with the inspection equipment functions is built. There the main function is divided in two functions in the second layer which inspect product properties on the one hand and supporting/enabling product inspection on the other hand.

In **phase 4** one or more solution elements for every function in the functional hierarchy is searched and structured in an extended morphological box. The characteristic of this extended morphological box is the spanning of the minimal and maximum solution space, e.g. for the multiple functions from 1 to *m***n* solution elements. Thereby a three dimensional morphologic box is created. In order to evaluate the best overall solution different paths are built through the morphological box, which are reasonable from a technical point of view. These paths are solution alternatives for the overall inspection equipment. Then these paths are evaluated by the non–functional requirements and the best path is selected. In **phase 5** a principle solution for the inspection equipment is built by an active structure (cf. Fig. 2). While in phase 1 the system (inspection equipment) was watched as a black box, in this phase the environment model is complemented by the elements from the morphologic box into the black box. Therefore all elements, environment elements and system elements are connected with relation arrows. In **phase 6** an overall sketch of the inspection equipment is built from the selected solution elements of the morphological box, which are figure relevant and needed for further considerations.

4. Application Example

The Karl E. Brinkmann Company (KEB) is a manufacturer of drive and automation technology, in particular of frequency converters and DC-AC-Inverters [39]. The focus of an current project in cooperation with KEB as part of the Leading-Edge Cluster *it's-OWL* is the design and development of an innovative modular inverter system (IMIS) [7]. This IMIS has to supply auxiliaries in commercial vehicles such as buses, trucks, municipal vehicles and agricultural machinery such as tractors, harvesters, attachments and construction machines like excavators, bulldozers and steamrollers. Examples for auxiliaries are air compressors, fans, hydraulic pumps, coolant pumps, air compressors and attachments. The advantage of the electrical supply is that they are no longer directly coupled to the rotation speed (rpm) of the combustion engine. Because of the different required number of auxiliaries in various vehicles, the IMIS is a

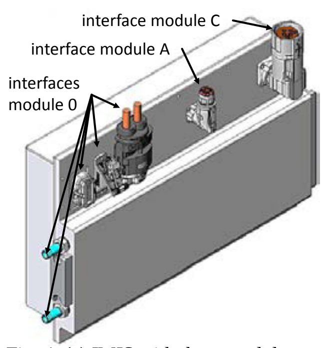


Fig. 4. (a) IMIS with three modules

modular system with the module types 0, A, B, C and extra module. Each IMIS has one module 0, the head-module, with the power connection, communication connections and cooling liquid connection. The module types A, B, C have the same main functions, but different maximum power outputs (A≙max. 7,5 kW; B≙max. 15 kW; C≙max. 30 kW). The customer can configure his own configuration using the different module types. In Fig. 4a an IMIS with the configuration 0-A-C is shown. Furthermore, the IMIS offers additional functions such as inputs for temperature sensors to measure the temperature of the electrical engine.

From the development point of view phase 3 of Fig. 3a contains the biggest enhancement. Consequently, the following description mainly refers to this phase 3. During the project a lot of functions were identified. An overview shows the high complexity and variety: 15 optional functions; one alternative function with two sub-functions; three multiple functions with 14, respectively 9, respectively 27 sub-functions; totally minimum there are circa 200 functions (no multiple sub-functions and no optional functions are counted); totally maximum there are more than 500 functions (all multiple sub-functions and optional functions are counted). In order to structure the solutions in the morphologic box in a systematic way in a first step a superstructure was built. Generally the main function "Production end inspection" (F1) was divided into two parts: the "Inspection of module properties" (F1.1) which is the main reason to build the inspection equipment and the auxiliary functions labeled as "Enable IMIS inspection" (F1.2). The number of dots shows the depth of the functions in the functional hierarchy.

These auxiliary functions are necessary to run the inspection system in an efficient and safe way. Examples of auxiliary functions are "Avoid unauthorized access" (F1.2.9.5) and "Adjust voltage measurement" (F1.2.6.1.2).

The function "Production end inspection" (F1) is divided into several sub-functions of the superstructure. The aim of this structure approach is to allocate the several needed functions to the modules of the product. For example function F1.1.2.2 includes all functions of the inspection equipment inspecting functions that are included in each of the modules A, B, C. Examples for that are the "Inspection of motor temperature measurement" (F1.1.2.2.1.1.) and the "Inspection of rotational speed in nominal operating point" (F1.1.2.2.2.1.4). Both of these functions are included in every produced module from type A, B or C.

As the multiple function has a special importance, exemplarily the calculation of the minimum and maximum number of the multiple function according Table 1 is explained. The function "Inspection of motor temperature measurement" has to inspect if the IMIS measures the right temperature (if a temperature sensor is connected to a module A, B, or C). So it is possible to use one solution of the inspection function, for example a sensor simulator, for one IMIS. In this case this single sensor simulator has to be switched from one module to the next of one IMIS. Another case can occur so that there has to be a sensor simulator for every module from Type A, B or C to inspect these modules of one IMIS parallel for example in order to save inspection time. In this case $m = 7$ because the maximum number of modules of one IMIS is 7. A further case can appear so that $n = 4$ IMIS has to be inspected in parallel, for example to save more inspection time. In that case $m*n = 7*4 = 28$ sensor simulators are needed.

Referring to the example, this procedure shows a way from a product design to an inspection system and demonstrates the solution space. It helped to find and structure solutions - to calculate the number of possible, needed and wise solution elements. It assists to generate a structured view on the inspection system in an early development phase. Particularly the early involvement of the department R&D Manufacturing Equipment was very helpful for KEB. The procedure was evaluated to be helpful for KEB and will be used for further work.

5. Conclusion and Further Work

Conclusion: Inspection equipment assures the product quality at the end of the production. This equipment is often – likewise – a mechatronic system, which is developed to inspect a specific product in different configurations. This paper describes an approach to adapt the inspection equipment to a modular system and describes how to design the inspection equipment in a modular way by itself. This approach allows an integrative development of product and inspection equipment with the help of MBSE, starting in an early development phase, which has not been possible in this way before.

Future work: The added values of the integrative development process are the identification of the product requirements from the inspection system. Moreover, the inspection equipment will be available at the SoP. In order to achieve this phase 3 of Fig. 2b, phase 3 has to be described in detail and elaborated as described in chapter 3.

Acknowledgements

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